

## SCIENCE & TECHNOLOGY OFFICE



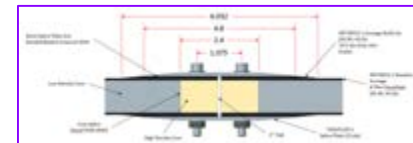
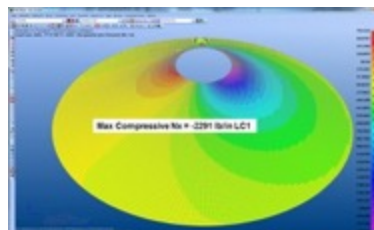
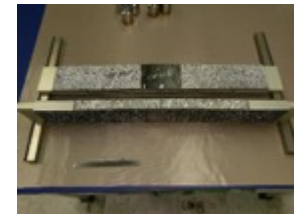
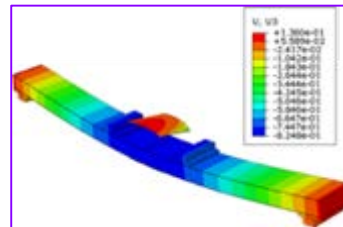
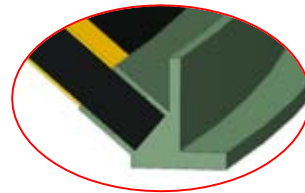
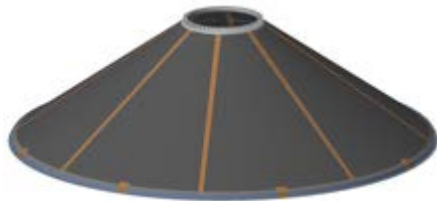
# Composite Technology for Exploration (CTE)

## Briefing to RUAG May 22, 2018

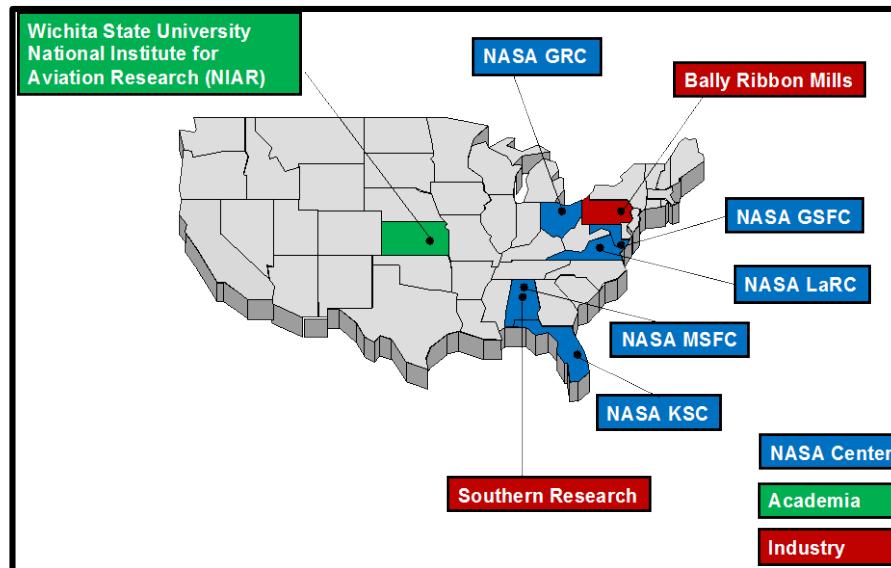
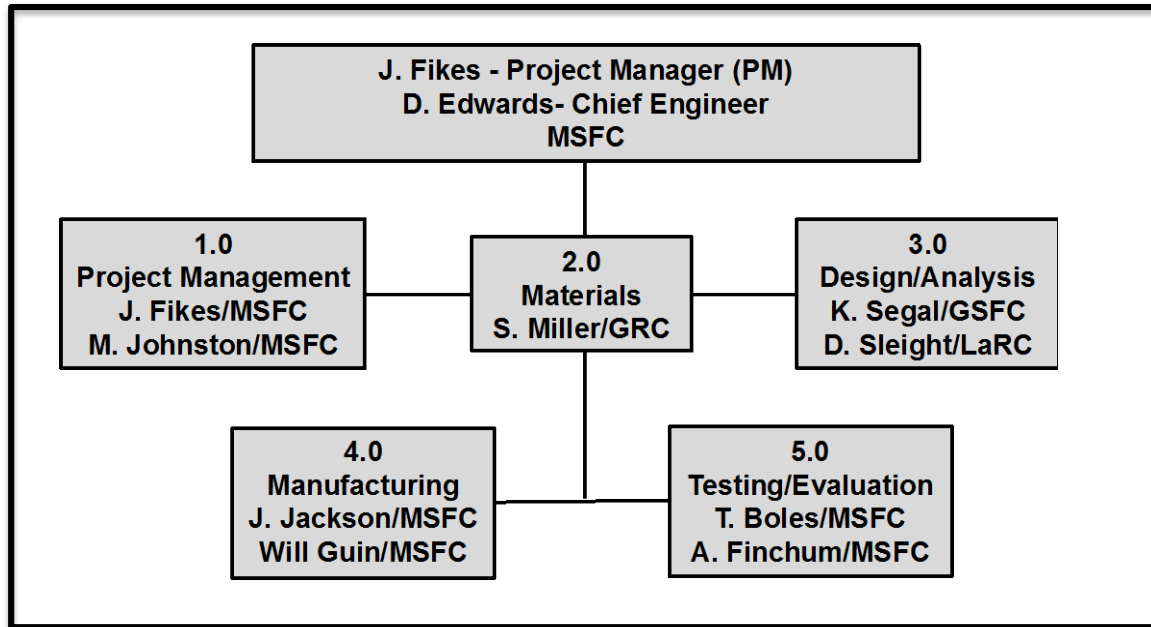
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## • Technology Product Capability

- The CTE project will develop and demonstrate critical composites technologies with a focus on weight-saving, performance-enhancing bonded joint technology for Space Launch System (SLS)-scale composite hardware to support future NASA exploration missions.
  - Improve the analytical capabilities required to predict failure modes in composite structures.
  - Support SLS payload adapters and fittings by maturing composite bonded joint technology and analytical tools to enable risk reduction.



# Composite Technology for Exploration (CTE) Organization and Key Members



## Level 1 Project Goals

### Composite Technologies for Exploration (CTE)

#### Goal #1

Develop and validate high-fidelity analysis tools and standards for predicting failure and residual strength of composite bonded joints.

#### Goal #2

Develop and demonstrate an analytical tailoring approach that enables the reduction of the baseline 2.0 safety factor for composite discontinuities.

**Notes:** The CTE longitudinal joint design was selected to be a double lap, out of autoclave/out of oven cured bonded composite joint. Fabricated and tested panels of IM7/8552-1 that successfully demonstrated equivalency to the NCAMP database. Completed fabrication of 30 acreage sandwich panels to be used for bonded joint development. Procurements in place with Bally Ribbon for circumferential joint 3-d weave material. Developed process parameters to utilize hot bonder for curing bonded joint. Developed longitudinal joint detailed designs, test article designs and NDE standards. Evaluating bonded circumferential joint concepts. Developing and evaluating different analysis tools including a parametric FE-based joint design tool, global/local FE models for joint strength and buckling, joint sub-element FE models for test validation and cohesive zone and VCCT longitudinal joint specimen models for prediction of joint failure. Starting coupon testing at Southern Research.

## Key Technology Challenges

### Composite Technologies for Exploration (CTE)

Title	Description
<b>Joint Configuration</b>	Identify low mass bonded joints for fiber composite launch structures
<b>Model Predictions</b>	Establish modeling capabilities that failure predictions of empirical data with low engineering uncertainty.

**Notes:** The CTE project has designed a bonded (no fasteners) longitudinal joint. Joint test coupons will be fabricated and tested and full-scale joint tests will follow. Next, the CTE project will design a bonded circumferential joint – much bigger challenge, but much bigger payoff.

The CTE project has down-selected several analytical programs and failure theories. The project is currently analyzing joint designs with selected programs and theories. Results of joint tests will be used to evaluate analytical approaches.

## Key Performance Parameters

### Composite Technologies for Exploration (CTE)

Performance Parameter	State of the Art (SOA)	Threshold Value	Project Goal	Estimated Current Value
Failure Prediction <sup>1</sup>	±25% of mean	±15% of mean	±5 of mean.	See 1.0 in notes
Risk Reduction Factor <sup>2</sup>	2.0	1.8	1.4	SOA
Part Count <sup>3</sup>	100%	75%	50%	SOA
Weight <sup>3</sup>	100%	85%	75%	SOA

#### Notes:

1.0 Initial assessment of advanced tools by experienced analyst reflects reduction to threshold value of ±15% of mean.

2.0 Safety for joints in primary load path for an SLS-like composite structure Discontinuity Factor of Safety =  $J \times 2.0$ , where  $J$  is a risk reduction factor based on new analytical techniques and test data.

3.0 State of art metal bolted joint in primary load path for 8.4 M diameter scale structure. Weight associated with metal/bolted joints (*e.g., 3 lb/ft metal bolted joint to lower weight per linear foot bondline*)

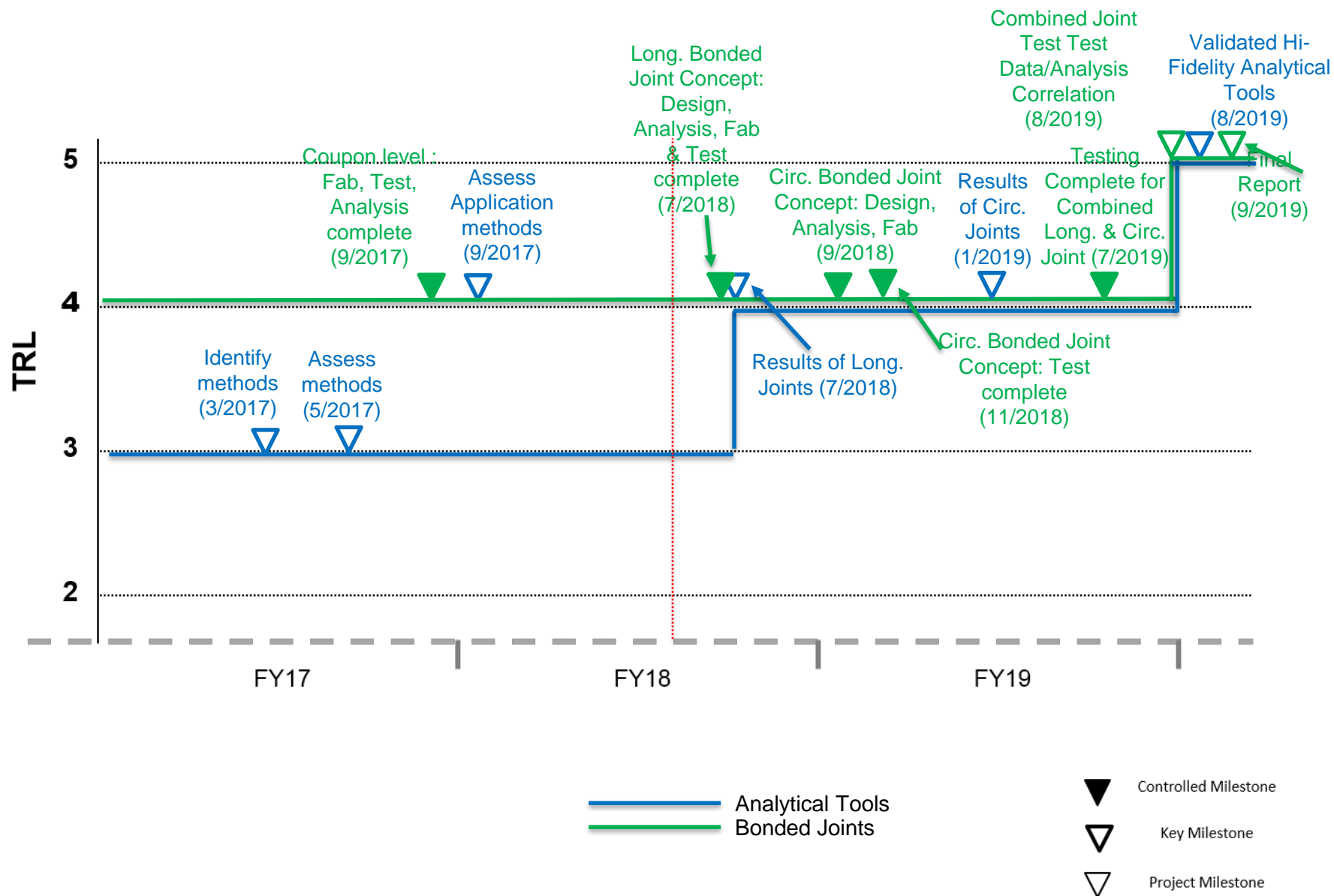


FY17:	Status
Report- Evaluation of Prior Program & Project Composite Joint Activities for Lessons Learned	✓
OoA Material down select & Procurement	✓
Down select of Longitudinal Joint Design Concept for SLS Specific application (i.e. EUS, PAF)	✓
Report- Material Equivalency Testing & Analysis of IM7/8552-1	✓
Complete Fabrication, Testing & Data Analysis for Coupon Level Material Development	✓
Report- Correlation of Digimat Computational Models with Material Property Test Data	✓
Report- Assess, Apply & Compare Bonded Joint Strength Prediction Methodologies	✓
Report- Application & Implementation of New Manufacturing Process Control and NDE Technologies	✓
Report- Shell Buckling Knockdown Factor (SBKF) Sensitivity Analysis	✓

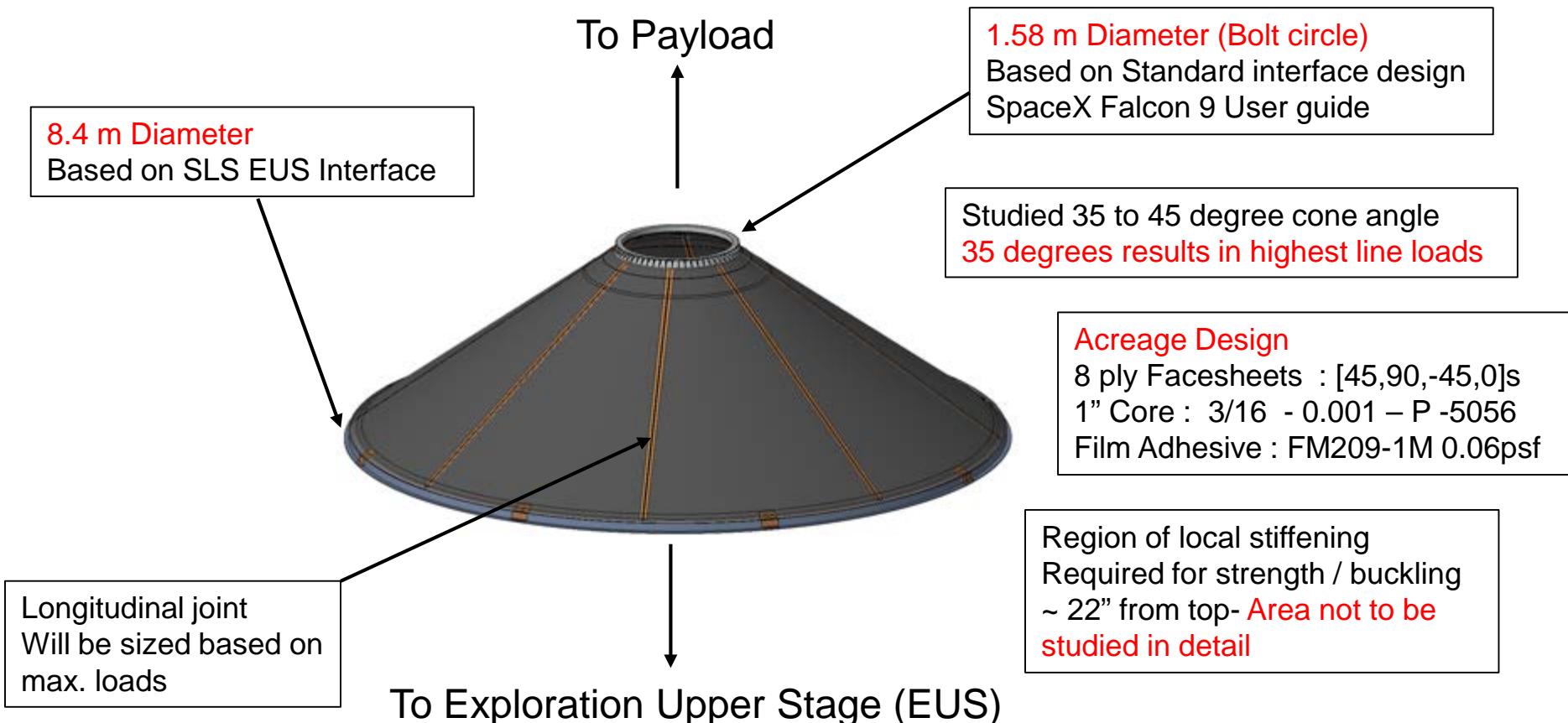
Milestone Title	Estimated Completion Date
Complete Design, Analysis, Fabrication & Testing of Down Selected Longitudinal Bonded Joint Concept (API)	8/24/18
Complete Circumferential Bonded Joint Concept Design, and Analysis	8/23/18
Report- Results of Longitudinal Joint Design, Manufacturing, Analysis & Testing	9/24/18
Complete Design, Analysis, Fabrication & Testing of Large-Scale Longitudinal Bonded Joint Concept	9/28/18
Complete Design & Analysis of Combined Joint Test Articles and Test Fixtures	9/4/18
Report – Application & Implementation of New Manufacturing Process Control and NDE Technologies	9/14/18



# Composite Technology for Exploration (CTE) TRL Assessment



- CTE Point Design Developed
  - Sized CTE point design configuration based on provided loads, assumed interfaces, and geometry relevant to SLS-scale composite structure.



- Re-certification Test Matrix

- A prepreg material which has exceeded its recommended freezer life may be 'recertified' through a user defined set of chemical and mechanical tests.
- There are no defined community standards for recertification, however test should represent the types of quantifiable changes that would be expected as a material ages; such as physical properties and resin dominated mechanical performance.
- CTE derived 95% confidence interval was used to establish pass/fail criteria for recertification.

The CEUS material shelf life expired in Sept 2016. Through this effort the material life is extended 12 months for CTE use; beginning from the date of panels fabrication, February 2017.

Compression Panel	Lay-up	Test Standard	Batches	Panels/ Batch	Panel Total	Specimen/ Panel	Specimen Total
Compression Strength and Modulus	[0] <sub>12</sub>	SACMA SRM 1	2	1	2	5	10
Fiber Volume	[0] <sub>12</sub>		2	1	2	5	10
Short Beam Shear	[45/0/-45/90]3s	ASTMD2344	2	1	2	5	10
Tg by DMA	[45/0/-45/90]3s	ASTM D7028	2	1	2	2	4

## Objective:

Fabricate and test panels of IM7/8552-1 to demonstrate equivalency to the NCAMP database.

## Key Accomplishment/ Deliverable/Milestone:

- Fabricate, Inspect and Test Panels.
- Statistical analysis for equivalency.

## Significance:

- Successfully demonstrated equivalence to the NCAMP database; allowing the data to be leveraged as needed.
- Demonstrated comparable mechanical properties between parts fabricated at Langley and Marshall. This is significant as both centers have manufactured acreage panels for joint tests.
- Demonstrated retention of material processability and properties following extended freezer storage; expanding upon the re-certification effort.

Test	Property	Environmental Condition			
		RTD		ETW	
		Langley	Marshall	Langley	Marshall
Longitudinal Compression	Modulus	Pass	Pass	Pass	Pass
Transverse Compression	Strength	Mild Failure	Pass	Mild Failure	Pass
	Modulus	Pass	Pass	Mod. Failure	Mod. Failure
Longitudinal Tension	Strength	Pass	Pass	Pass	Pass
	Modulus	Pass	Pass	Mild Failure	Pass
Transverse Tension	Strength	Pass	Pass	Pass	Pass
	Modulus	Pass	Pass	Pass	Pass
In-Plane Shear	0.2% Offset Strength	Mild Failure	Mild Failure	Pass	Pass
	5% Offset Strength	Pass	Pass	Pass	Pass
	Modulus	Pass	Pass	Pass	Pass
Un-notched Compression	Strength	Pass	Pass	Pass	Pass
	Modulus	Pass	Pass	Pass	Pass
Un-notched Tension	Strength	Pass	Pass	Pass	Pass
	Modulus	Pass	Pass	Pass	Pass
Open-Hole Compression	Strength	Pass	Pass	Pass	Pass
Open-Hole Tension	Strength	Pass	Pass	Pass	Pass
Filled-Hole Tension	Strength	Pass	Pass	Pass	Pass
Single Shear Bearing	Strength	Pass	Pass	Pass	Pass

## Fabrication, Testing & Data Analysis for Coupon Level Material Development

### Objective:

Fabricate and test panels of T650 PW/5320-1 joint material to generate data not available in databases.

### Key Accomplishment/ Deliverable/Milestone:

- Fabricated and Inspected Test Panels.
- Completed testing and Data analysis.

### Significance:

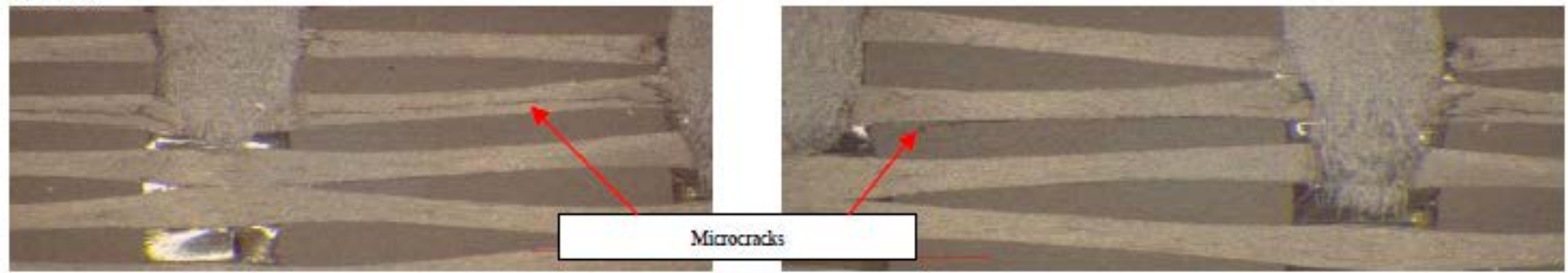
- Material data was needed to generate analysis models. The data provided within this milestone will be used for the global CTE analysis model to determine the stresses/strains in the doublers.
- Additional data will be provided for use in the cohesive zone and VCCT longitudinal joint specimen models for prediction of joint failure.

Test	Lay-up	CTE Data (CV %)	NCAMP data (CV %)
Longitudinal Tensile Strength (ksi)	[0]15	128.9 (1.5)	124.9 (4.8)
Longitudinal Tensile Modulus (Msi)	[0]15	10.1 (1.0)	10.0 (1.1)
Longitudinal Compressive Strength (ksi)	[0]15	116.4 (6.4)	106.2 (7.0)
Longitudinal Compressive Modulus (Msi)	[0]15	9.4 (2.0)	9.4 (1.9)
Longitudinal Tensile Strength (ksi)	[+45, -45]3s	37.3 (2.4)	not reported
Longitudinal Tensile Modulus (Msi)	[+45, -45]3s	2.5 (2.0)	not reported
Longitudinal Compressive Strength (ksi)	[+45, -45]3s	33.7 (2.8)	not reported
Longitudinal Compressive Modulus (Msi)	[+45, -45]3s	2.5 (1.2)	not reported
In Plane Shear Strength (0.2% offset) ksi	[+45, -45]3s	8.0 (1.3)	8.3 (1.6)
In Plane Shear Strength (5% offset) ksi	[+45, -45]3s	14.0 (1.4)	14.7 (3.1)
In Plane Shear Strength (max strength) ksi	[+45, -45]3s	18.8 (2.7)	not reported
In Plane Shear Modulus (Msi)	[+45, -45]3s	0.7 (1.8)	0.7 (1.7)]
Short Beam Shear	[0]32	11.5 (2.7)	11.0 (3.7)

CTE and NCAMP values represent 'as measured' data and are not normalized for fiber volume

The purpose of the flat panel study includes:

- (1) Risk reduction by providing material data to design and analysis
- (2) Evaluation of resin micro-cracking in the 3D woven architecture



Ref: Sonaca, SAMPE Long Beach 2016

Procurements initiated:

Bally Ribbon Mills: manufacture 3D woven preforms; 2'x2' flat panels.

North Coast Tooling: RTM processing for flat panels

NIAR/NASA: Mechanical Tests



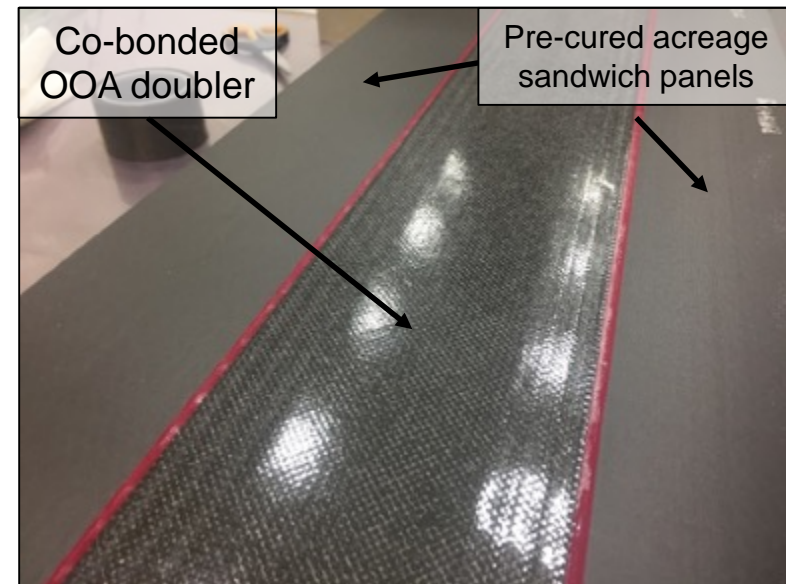
- **Completed fabrication of 30 acreage sandwich panels to be used for bonded joint development**

- 15 fabricated at MSFC; 15 fabricated at LaRC
- 2' x 4' sandwich panels
- Facesheets: IM7/8552-1 slit tape,  $[+45/90/-45/0]_s$  layup
- Film adhesive: FM209-1M
- Core: 3.1 pcf, 5056, 3/16" cells, 1" thick



- **Completed fabrication of 10 bonded joint assemblies for edgewise compression testing**

- Bonded doublers: T650/5320-1 out-of-autoclave (OOA) plain weave fabric (4 plies)
- Coupons will be sectioned from parent assemblies and tested with respect to pristine and damaged states





- **Developed process parameters for hot bonder**

- Powers heat blankets to replace oven for out-of-autoclave cure on large-scale components.
- Developed optimal cure parameters for CTE bonded joint materials.



Oven (finite volume limits ability to scale)



Hot bonder + heat blankets (capacity scales with blanket size)

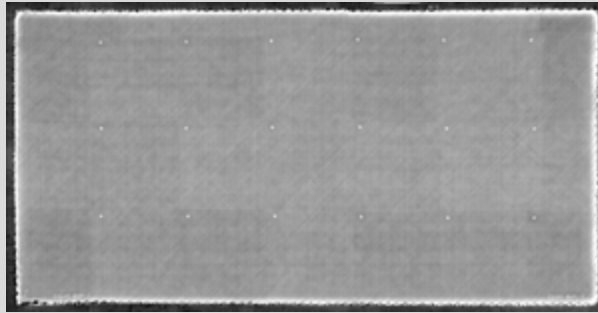
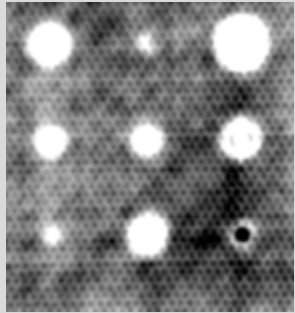
- **Will demonstrate bonded joints on Payload Adapter manufacturing demonstration article**

- Will use manufacturing processes and bonded joint design developed by CTE team on 4 longitudinal joints.
- Will demonstrate path to infusion from CTE to SLS.

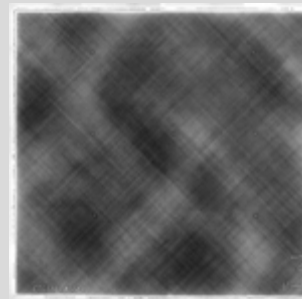


## Nondestructive Evaluation:

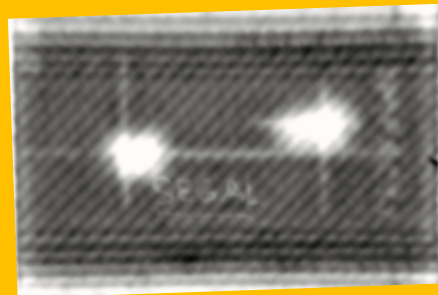
Examples of sandwich panels and laminate panels that have been inspected.  
Utilized Thermography (IRT) and ultrasound (UT)



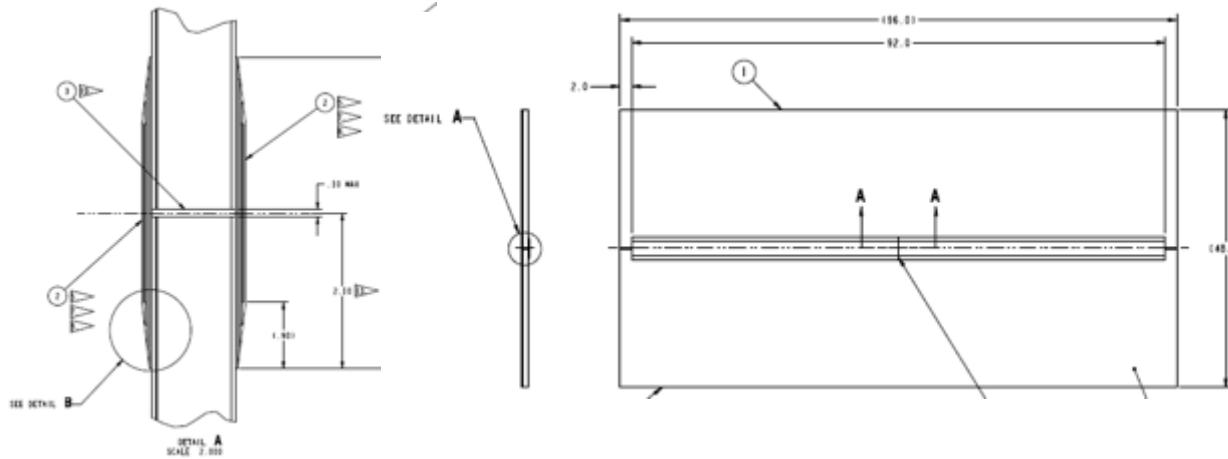
Standard Panel (left) with built-in defects was used to baseline techniques applied directly to full-scale panels (right) and correlate size, depth, and signature of any indications noted.



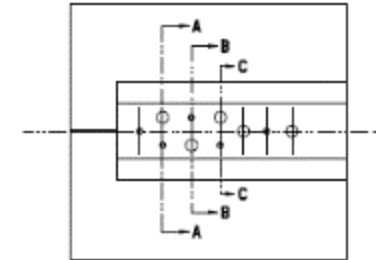
IRT (left) and UT (right) show similar sensitivity to low-level panel micro-structure variations.



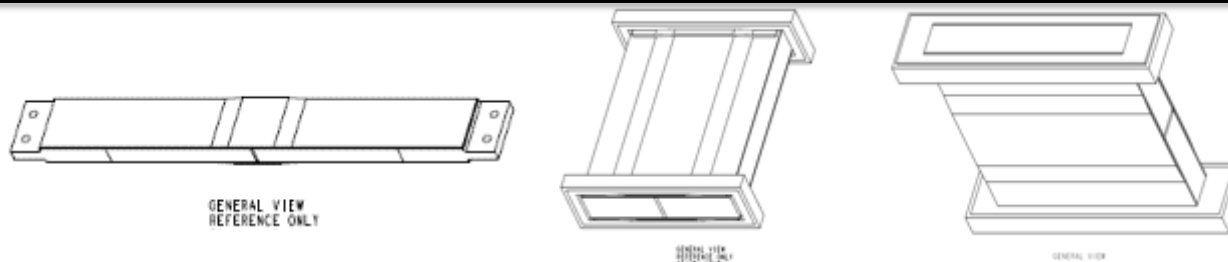
IRT impact damage extent characterization on bonded joint sample, part of a multi-method comparison study.



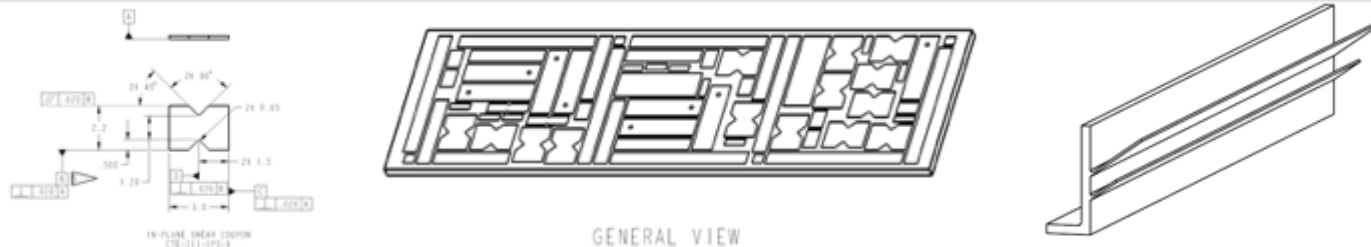
## Longitudinal Joint (L-Joint) Detailed Designs



# NDE Standards for CTE Panels and L-Joints



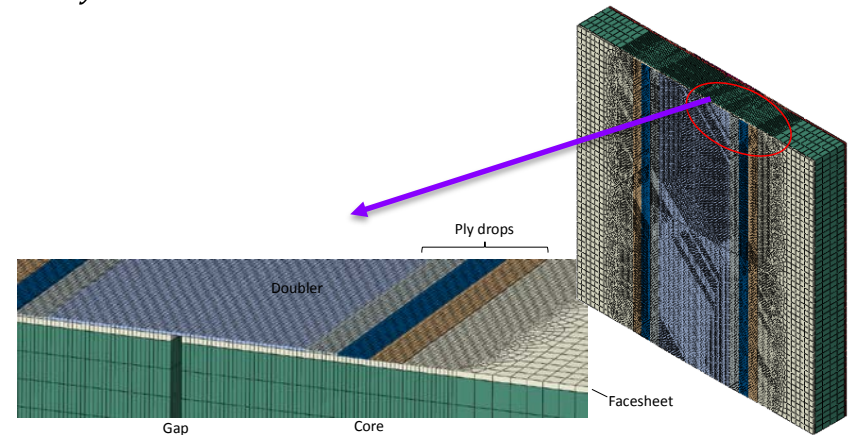
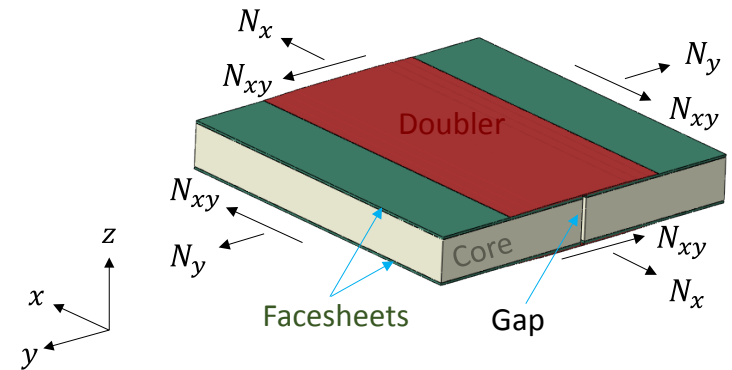
## L- Joint Test Article Designs



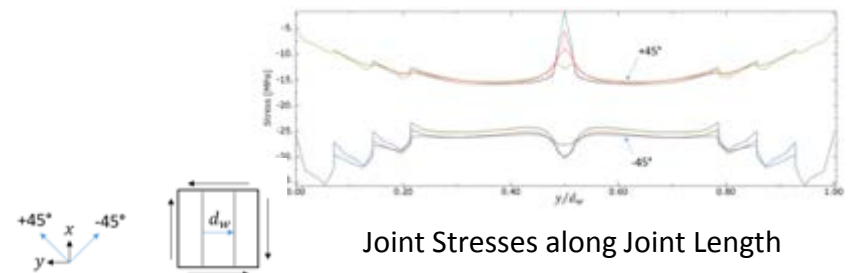
## 3D Woven Composite Test Coupon, Cut Plan and Part Designs

## Developing Parametric FE-based Joint Design Tool

- **Objective:** Design tool to size longitudinal joints that considers:
  - Combined line loads ( $N_x$ ,  $N_y$ ,  $N_{xy}$ )
  - 3-D stress state in core, facesheets, and doublers
  - Relevant design features: adhesive layer, ply drop off sequence, panel gap, and defects
- **Benefits**
  - Capture conditions that drive design: 3-D model with combined loads
  - Flexibility in the model to include geometric details (ply drops) and adhesive (with or w/o nonlinearity)
  - Compatible with any ply-level failure criteria
- **Future Work**
  - Compare results with A4EI, HyperSizer, and Joint Element Designer Tools



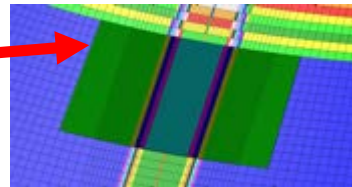
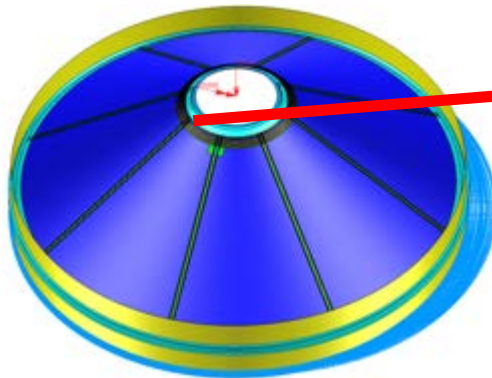
Joint Parametric FE Model



Joint Stresses along Joint Length

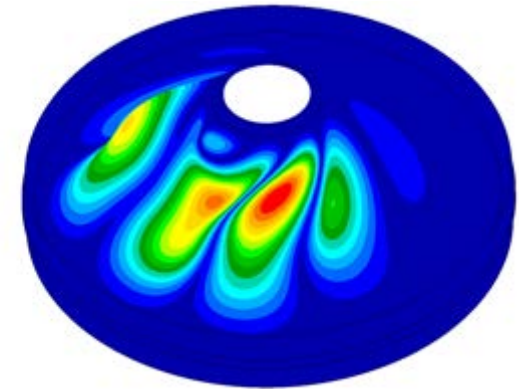


## Global/Local FE Models for Joint Strength and Buckling

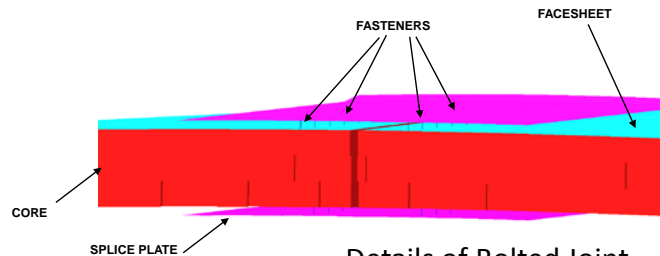


Detailed Local FEM  
(Overlaid on Global FEM)

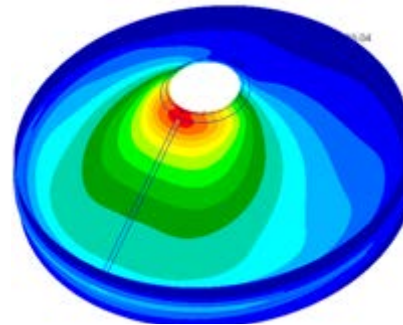
Global/Local Bonded Longitudinal Joint FEM



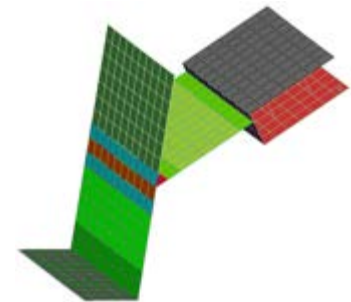
Buckling Mode Shape



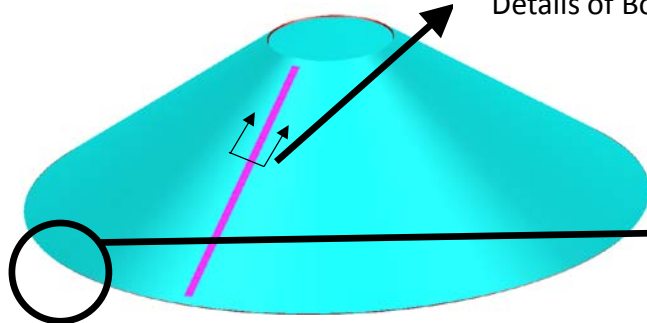
Details of Bolted Joint



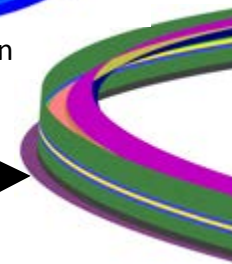
Deformation



C-Joint Details

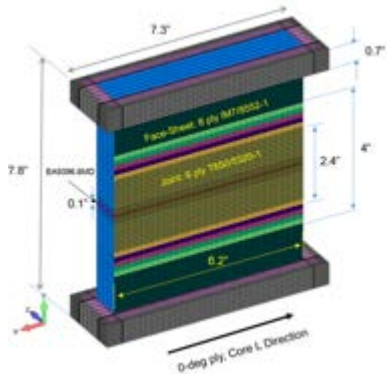


Global Bolted/Bonded Longitudinal Joint FEM

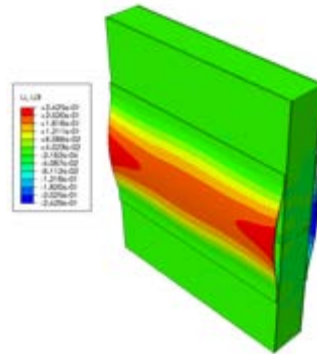


Global Bolted Circumferential Joint FEM

## Joint Sub-Element FE Models for Test Validation



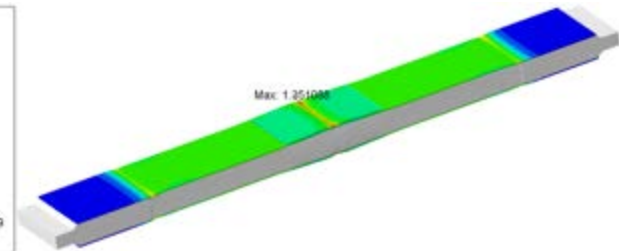
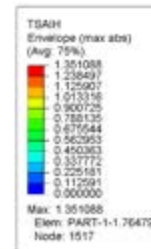
Hoop-wise Compression Bonded Joint Model (w/o Adhesive)



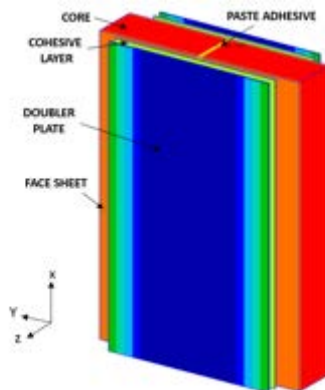
Hoop-wise Compression Bonded Joint (w/o Adhesive) Joint Failure



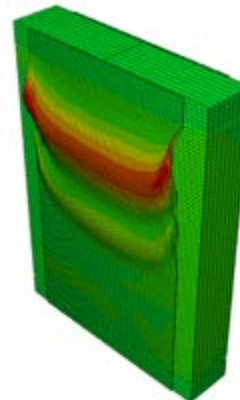
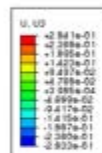
Hoop Tension Bonded Joint Half Model



Hoop Tension Bonded Joint Model Joint Failure



Edge-wise Compression Bonded Joint Model



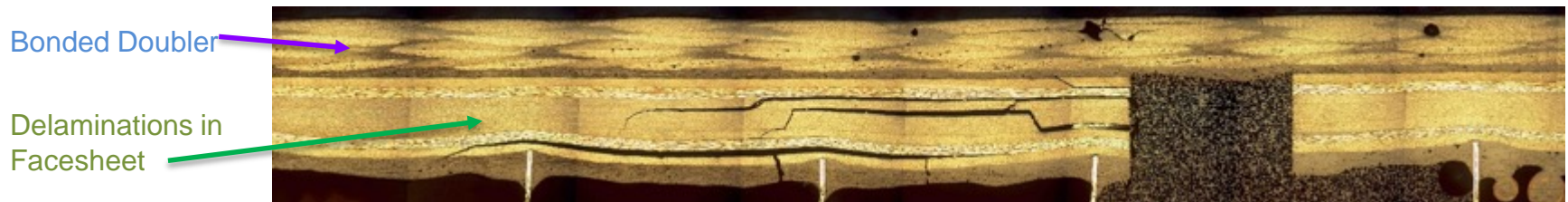
Edge-wise Compression Bonded Joint Model Failure in Facesheet

## Damage Testing

**Goal:** Test Barely Visible Impact Damage (BVID) panels to determine residual strength

**Accomplishments:**

- Performed Impact Survey to determine BVID Impact Energy Level
- Recommend 6 ft-lb Impact offset from the joint splice for the test panels



Cross Section View of Impacted Region (6 ft-lb)

## Repair Process Development

**Goal:** Develop repair concepts and requirements for a launch site repair

**Accomplishments:**

- Currently developing repair concepts based on observed impact damage to the joint



# Summary

- Completed report that documented the successful equivalency to the NCAMP database of IM7/8552-1 fabricated and tested panels.
- Completed fabrication of 30 acreage sandwich panels to be used for bonded joint development.
- Developed longitudinal joint detailed designs, test article designs and NDE standards.
- Coupon testing at Southern Research in progress.
- Procurement in place with Bally Ribbon for 3-d weave material for circumferential joints.
- Developing and evaluating different analysis tools including a parametric FE-based joint design tool, global/local FE models for joint strength and buckling, joint sub-element FE models for test validation and cohesive zone and VCCT longitudinal joint specimen models for prediction of joint failure.